According to the military purpose or the devices used.

Concerning the basic schemes of energy release, we can basically distinguish nuclear fission weapons and nuclear synthesis weapons.

Nuclear fission weapons are nuclear weapons in which the detonation energy is produced by the fission of heavy, energy-rich nuclei into heavy nuclei which are poorer in energy, in the process of thermonuclear reactions.

In keeping with the course and type of energy release, we can furthermore distinguish between single-phase and multi-phase nuclear weapons.

The term single-phase nuclear weapons is applied to those nuclear weapons where the energy release is based either only on nuclear fission or only on nuclear synthesis.

Multi-phase nuclear weapons are nuclear weapons where the detonation energy is released in succession through nuclear fission and nuclear synthesis reaction in two or three phases (nuclear fission--nuclear synthesis--nuclear fission).

Nuclear fission weapons and nuclear synthesis weapons thus are single-phase nuclear weapons corresponding to the concept definitions given here.

In using the terms mentioned we must keep in mind that no uniform terminology has so far prevailed both in military language and in the pertinent literature. For example, in place of the concept of multi-phase nuclear weapon: we still frequently have the concept of nuclear synthesis weapon or thermonuclear weapons although the energy from these nuclear weapons does not exclusively stem from nuclear synthesis.[3]

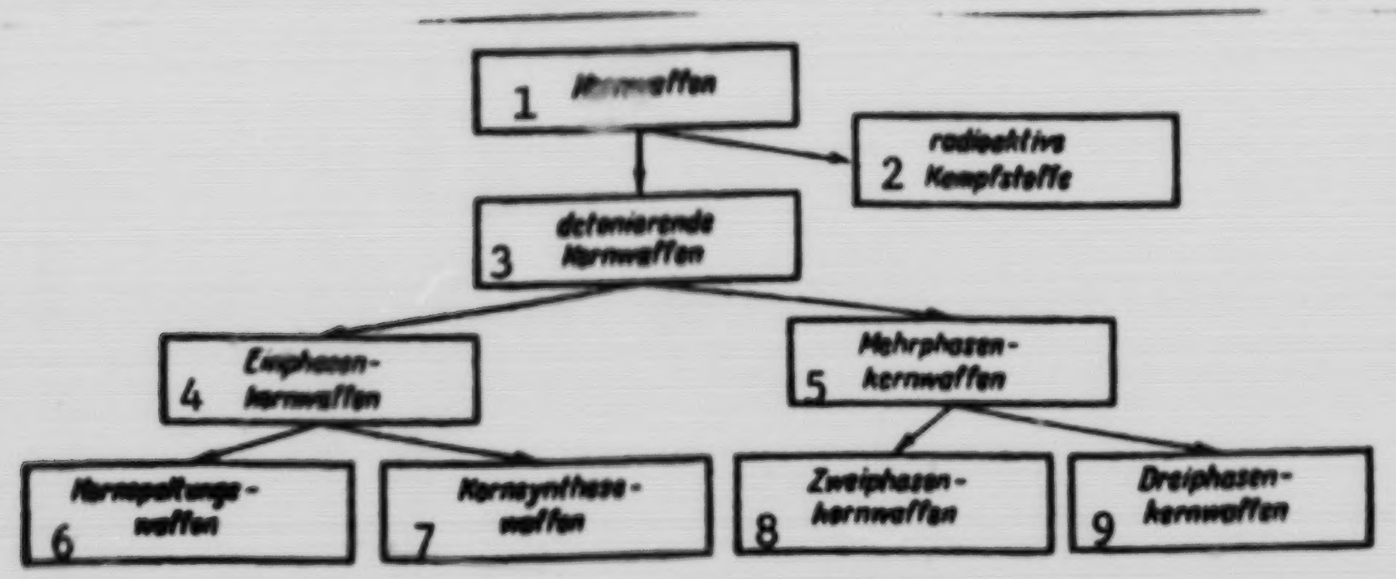


Figure 1.1. Classification of nuclear weapons in accordance with energy release. Key: 1--Nuclear weapons; 2--Radioactive warfare agents; 3--Detonating nuclear weapons; 4--Single-phase nuclear weapons; 5--Multi-phase nuclear weapons; 6--Nuclear fission weapons; 7--Nuclear synthesis weapons; 8--Two-phase nuclear weapons; 9--Three-phase nuclear weapons.

The detonation intensity is the most important characteristic of nuclear weapons.

The detonation intensity is a measure of the total energy released as a result of the detonation. It is given in equivalents (t, kt, Mt) of Trinitrotoluene (TNT).

In all formulas given in this book, the detonation intensity is always to be inserted in terms of kt TNT.

The detonation intensity of presently available nuclear weapons is roughly within the limits of 0.005 kt TNT to 100 Mt TNT.

This means that connection downward is established to the calibers of conventional ammunition. Upward, a further increase in the detonation intensity is physically and technically conceivable but militarily hardly meaningful.

We can schematically subdivide nuclear weapons as follows, as a function of the detonation intensity:

Small detonation intensities:	$q \leq 15$ kt TNT
Medium detonation intensities:	15 kt TNT $< q \leq$ 100 kt TNT
Large detonation intensities:	100 kt TNT $< q \leq$ 500 kt TNT
King-size detonation intensities:	$q >$ 500 kt TNT

The nuclear weapons criminally employed against Hiroshima and Nagasaki by the American imperialists in 1945 had a trotyl equivalent of about 20 kt. This detonation intensity is often used as a comparison value and is therefore referred to as the "standard bomb."

A detonation intensity of 100 Mt TNT implies an increase in the detonation energy at a ratio of 1:5,000.

In this kind of estimate one must however keep in mind that the annihilation radii do not grow simply in proportion to the detonation intensity but increase considerably more slowly. On top of that we furthermore have the fact that the detonation intensity, expressed in trotyl equivalents, is only a measure of the magnitude of the total energy released during a detonation whereas regarding the distribution of that energy over the individual annihilation factors, no simple comparison to conventional ammunition is possible.[4]

In purely physical terms, a smooth transition is possible in the range of detonation intensities mentioned here. Considering the tactical-technical data on nuclear weapons devices, we however get certain standard detonation intensities which make it possible to evaluate the consequences of enemy nuclear weapons strikes.

The type of nuclear charge used likewise does influence the characteristic of a nuclear weapon.

The radionuclides U-235 and Pu-239 are used mostly in nuclear fission weapons.

The hydrogen isotopes deuterium and tritium are used--mostly in the form of lithium compounds--in nuclear synthesis weapons or in multi-phase nuclear weapons.

U-238 is used for the release of nuclear fission energy by means of super-fast neutrons.

The nuclides that can be used for nuclear fission differ essentially in terms of their critical parameters. For example, the size of the critical charge mass of Pu-239 is only about 25 percent of that of U-235.

This necessarily results in differentiated design principles for the individual nuclear weapons types. On top of that we have the fact that nuclear explosives also differ greatly in terms of their miscellaneous physical and chemical properties. Something similar applies to nuclear synthesis materials. Here, for example, the aggregate state, in which they are normally present, plays a very great role. Another viewpoint is derived from the differing ignition temperature and the resultant highly variable course of thermonuclear processes as a function of the composition of the nuclear synthesis charge.

Some other viewpoints will be covered in greater detail in connection with the individual nuclear weapons types.

By way of guidance we might estimate that nuclear fission weapons of up to about 300 kt TNT can probably be made. In practice however the upper limit would be around 100 kt TNT. Two-phase nuclear weapons (addition of nuclear synthesis material) are best suited for detonation intensities of several hundred kt TNT. Nuclear weapons in the Mt range are most probably based on the three-phase principle. But it is also possible to bring about very great detonation intensities with a high nuclear synthesis share. Conclusions can be derived from several test series.

The means of delivering a nuclear charge to a target are very manifold. At the end of World War II and during the years immediately thereafter, nuclear weapons existed practically only in the form of bombs. Today, nuclear charges are delivered primarily by missiles. The combination of missile and nuclear weapon, the nuclear missile, represents a completely new quality of fire. It forges the technical character of a possible world war as a nuclear missile war. Prior development of weapons in engineering terms as well as nuclear warheads, as delivery vehicles or devices, makes it possible today to use nuclear weapons universally, over any desired range, against the most varied targets under all meteorological conditions.

Nuclear weapons can be used by all services. Specifically, they can be used in the following ways (some of the NATO devices are given in parentheses):

Ground-to-ground missiles for tactical, semistrategic, and strategic uses, with nuclear charge ("Lance"--up to 70 km, "Sergeant"--up to 140 km, "Pershing" --up to 740 km, "Minuteman"--up to 13,000 km);

Ground-to-air missiles (AA missiles to engage manned and unmanned air attack systems, ABM's) with nuclear charge ("Nike-Hercules"--30 km altitude);

Aircraft (nuclear bombs and air-to-ground missiles with nuclear payload) ("F 84 F Thunderstreak," "F-100 D Super Sabre," "F-4 C Phantom," "HSD Blue Steel" air-to-ground missile--up to 320 km after firing from aircraft);

Conventional artillery pieces (roughly from 150 mm on up) in the form of nuclear shells (155-mm SP howitzer, M-109, up to 18 km, 203.2-mm SP howitzer, M-110, up to 16 km);

Submarines, especially nuclear-powered, in the form of underwater--ground missiles with nuclear charge or torpedoes with nuclear charge ("Polaris" --up to 4,000 km);

Surface vessels with corresponding missile or torpedo armament;

Nuclear mines used by ground forces and naval forces;

Outer space systems.

The means for the employment of nuclear weapons to accomplish strategic assignments above all include intercontinental missiles, long-range missiles, but also medium-range rockets, strategic air units, and submarines as well as outer space weapons. Here one uses primarily nuclear weapons with detonation equivalents on the order of magnitude of several hundred kt TNT up to several tens of Mt TNT.

In the semistrategic-tactical context, short-range and medium-range rockets, fighter-bomber units, certain artillery systems, and mines are especially used as nuclear weapons.

Ground forces operations can partly be supported along the coastline through nuclear weapons employed by naval forces. The detonation intensities of semistrategic-tactical nuclear weapons as a rule cover a range extending from several kt TNT to several hundred kt TNT.

One special aspect of nuclear weapons development in recent years consists in the fact that the transition to multiple nuclear charges was accomplished especially in the strategic systems. In this way, several nuclear warheads can be aimed against one or several targets with a single delivery vehicle.

Although examples of this type become obsolete very quickly, we might mention here the American MRV and MIRV series systems. In the MRV system, for example, just one missile of the Polaris A-3 type can carry three nuclear warheads which, after their separation from the booster, reach their target in a ballistic form.

In the case of the MIRV system, the individual nuclear charges have an additional engine of their own and are used in a program-controlled manner against individual targets within a radius of up to 200 km.

The "Minuteman" can thus carry three nuclear warheads at 200 kt TNT, each, while the "Poseidon" can carry ten nuclear warheads at 50 kt TNT, each, including as many as four decoys.[5]

The most effective nuclear defense measure consists in annihilating enemy nuclear weapons systems before they are in a position to use nuclear weapons.

This goal requires specific knowledge of the employment principles of enemy nuclear weapons, their storage, movement, supply, etc., their constant observation and a readiness immediately to engage them after the appearance of such a target, using all available means, especially the systems of the rocket forces and the artillery on duty.

As we hinted earlier, nuclear weapons systems are constantly changing. Because, other things being equal, the annihilation effects of a nuclear weapon are relatively independent of the delivery vehicles, questions connected with that will not be subjected to any further consideration below.

Review Questions

1.1. What viewpoints must be considered in the concept definition of mass annihilation weapons?

1.2. What are the characteristics according to which we can arrange nuclear weapons and what practical conclusions can be drawn from that?

1.3. Why is the detonation intensity of a nuclear weapon not simply comparable to the effect of conventional weapons?

1.4. What kinds of nuclear weapons systems are presently available to NATO and what are the resultant conclusions concerning unit nuclear defense?

1.5. What is the most important nuclear defense measure and how can it be implemented.

1.2. The Most Important Stages in the History of Nuclear Weapons

The physical, chemical, and engineering prerequisites for the creation of nuclear weapons in the middle of this century were the numerous outstanding results from the natural sciences, especially atomic and nuclear physics, and the very highly-developed industry in the Soviet Union and in the leading imperialist countries.

The actual early history of nuclear weapons begins in December 1938 with the discovery of atomic nuclear fission through the action of neutrons by the German physicist Otto Hahn.

Theoretical studies conducted after this discovery already in 1939 revealed that tremendous quantities of energy could be obtained on the basis of nuclear fission under certain prerequisites. Until that time, by far most of the physicists were of the opinion that practical utilization of nuclear energy was not possible because the energy amount to be used for nuclear conversion was greater than the amount released as a result.

Hahn's discovery put the entire situation into a completely new light.

If we look at the international political situation at that point in time, we can understand that all further publications were suddenly cut off. In secret however physicists in a whole series of countries looked into the phenomenon of nuclear fission and also tried to fathom the resultant consequences.

These consequences could indeed be monstrous because after all German fascism was already getting ready to implement its aggressive goals by unleashing a world war.

In the United States, a group of scientists, headed by L. Szilard, persuaded Albert Einstein to contact President F. Roosevelt and to explain to him the military significance of the discovery of nuclear fission through neutrons and to propose the conduct of secret research.

Practical work on the "Manhattan Project" finally began in August 1942. This was the code name for all scientific, technical, military, and administrative measures which in the end were supposed to lead to the construction of a nuclear bomb and its employment.

During the 1940's, the United States had become a stronghold of nuclear physics. A. Einstein had emigrated from Germany while E. Fermi and E. Segre had come from fascist Italy. Nils Bohr came from Denmark. On the basis of this tremendous scientific capacity, backed up by a highly-efficient, undestroyed industry, work quickly progressed in spite of tremendous natural-science and technical difficulties. Los Alamos, the R. Oppenheimer laboratory, became the center for the design and construction of the bomb.

In addition to those already mentioned, Oppenheimer had working with him such well-known scientists as E. O. Lawrence, J. Dunning, and H. Bethe.

To obtain the necessary nuclear explosive, efforts were relatively quickly concentrated on three of the original five methods contemplated.

On 2 December 1942, Fermi recorded the first chain reaction in the graphite pile built by him.

On the basis of lessons learned until then, four big breeder reactors were built in Hanford, Washington, to produce Pu-239. The first plutonium shipment went to Los Alamos in January 1945.

Huge installations for the separation of the uranium isotope U-235 (share 0.7 percent) were built in Oak Ridge, Tennessee. A gaseous diffusion plant and an electromagnetic separation plant were built. The gaseous diffusion plant began to operate in January 1945 (at a cost of more than M1 billion); the enriched U-235 was then further processed in the electromagnetic plant so that an adequate quantity of U-235 was likewise ready for shipment to Los Alamos in June 1945.

By the middle of the year, the United States finally had three "atomic bombs." The sum of $2 billion was invested to attain this goal.

The first experimental detonation of a nuclear fission bomb based on the implosion principle took place at 0530 on 16 July 1945 at the Alamogordo Air Base in New Mexico. The detonation intensity of the 214-t experimental device, which was set off on a 30-m high steel tower, was 10 kt.

This first experimental detonation was followed on 6 and 9 August 1945 by the senseless and criminal bombing by the American imperialists on the two Japanese cities of Hiroshima and Nagasaki.

The nuclear detonations caused fearful losses among the defenseless and unknowing population.

Table 1.1. Effects of Nuclear Bombs Dropped on Hiroshima and Nagasaki[7]

		Hiroshima	Nagasaki
1	Gesamtbevölkerung	300000	200000
2	Bevölkerungsdichte je km^2	14000	25000
3	Tote	80000	40000
4	Verletzte	70000	40000
5	sofortige Erste Hilfe brauchten	85000	50000
6	Todesrate je zerstörten km^2	6000	8000

Key: 1--Total population; 2--Population density per km^2; 3--Dead; 4--Injured; 5--The following required first aid; 6--Death rate per km^2 destroyed.

Other figures were given in various publications. This is due to the fact that, because of wartime events, no precise data were available on the population statistics for both cities; besides, it is very frequently impossible to determine under what conditions the loss estimates were made.[8]

The size of the total area destroyed in Hiroshima was about 12 km^2 and in Nagasaki it was about 5 km^2.

The report by the United States Strategic Bombing Survey[9] among other things contains the following passage on the Hiroshima and Nagasaki raids: "A single atomic bomb was detonated at 0815 (0915 local time, Tinian time--the Author) on 6 August 1945 over Hiroshima. Most industrial workers had already started work but many were still on their way; almost all school children were busy putting up firebreaks or moving valuables out into the country.

"The raid took place 45 minutes after a prior all-clear. Because no air raid alarm was sounded and because the population in view of the few aircraft did not feel particularly worried, the detonation came as an almost complete surprise. Most people were taken by surprise out in the open or at home. The bomb blew up somewhat northwest of the city center. Because of the accurate bombing, the level terrain, and the circular layout of the city, Hiroshima was

devasted uniformly and comprehensively. The entirely heavily built-up part of the city was practically levelled to the ground due to blast and fire. A firestorm arose. And, 3 days later, Nagasaki was hardly any better prepared. The day was clear, there was almost no wind--a usual summer day. The continuing air raids against the population of the city and the harshness of the summer led to a certain neglect of air raid protection measures. The preliminary alert was sounded at 0748 and it was followed by the alarm as such at 0750; the all-clear was sounded at 0830 and the population's alertness yielded to a great feeling of calm. The city continued on the alert; but the air raid alarm was not sounded immediately when two aircraft of the B-29 type were sighted once again. The bomb was dropped at 1102 and the alert was not sounded until 1109. Only 400 persons were in the air raid shelters. At ground zero, almost everything had been levelled to the ground; no further reports came from that area immediately after the detonation."

In his memoirs, which were published in 1956, Truman--who as President of the United States at that time ordered the nuclear bombs to be dropped on the two cities of Hiroshima and Nagasaki--wrote the following: "In 1945, there took place so significant an event that our relations with the entire world were basically changed and that a new era was announced to mankind, an era whose consequences, as well as the objectives and problems it raised, we still cannot fully gauge at this time. This event is the production of the atomic bomb."[11]

What, in the view of American imperialism, was the essential content of these new relations?

Yesterday as today the imperialist circles in the United States try to explain that the rapid development of the American nuclear weapons system was necessary to get ahead of fascist Germany and that the use of the nuclear bombs against Japan supposedly forced that country into rapid capitulation and thus put an end to World War II.

If we follow the rational core of the investigations by D. Irving[12] concerning research in the field of nuclear weapons in fascist Germany and in the United States during World War II, we may, in the light of present-day knowledge, admit that some of the scientists involved in the Manhattan Project in their work were guided by concern over the fate of humanity threatened by fascism.

But this approach is only half the truth. Very soon, those scientists lost every right to have any say on the use of their work results.

Concerning Japan's capitulation, it was speeded up inasmuch as certain circles in the Japanese government which were inclined toward capitulation in this way with renewed clarity received a demonstration of the hopelessness of the military situation. This capitulation however in the final analysis was the result of the Soviet Union's entry into the war against Japan and the smashing of the main body of the Japanese army, the Kwantung army, in Manchuria. This clearly shows that the leading circles in the United States were quickly concerned with testing the new weapon under "specific" conditions and thus to tackle far-ranging political objectives.

The British physicist Blackett mentions these objectives as he writes that "dropping the atomic bombs was not so much the last military act of World War II but rather one of the first major operations in the cold diplomatic war against the Soviet Union."[14]

In view of the effects of these detonations, the leading circles in America at that time adopted the mistaken belief that "by threatening to use the atomic bomb, it would be possible to force the Soviet Union--no more and no less-- to drop socialism and to restore capitalism."[14]

It thus becomes clear with brutal openness that it was not so much America's fear of having Hitler Germany get ahead of it in the production of the first nuclear weapons which caused the American effort to make a maximum effort but rather from the very beginning the endeavor to use this new weapon as a means of threatening and blackmail and thus to carry out the United States' plans for world rule.[15]

Former President Truman did not feel any remorse later on over the fact that he gave the order to wipe out more than a hundred thousand innocent people in Hiroshima and Nagasaki. Early in November 1961 he made the hideous statement in addressing the National Press Club in Washington to the effect that he would at any time repeat the order to drop atomic bombs on both of these Japanese cities.[16]

The trotyl equivalent of each of the two nuclear bombs dropped on Hiroshima and Nagasaki was about 200 kt (20,000 t). But the previously mentioned report by the United States Strategic Bombing Survey shows that formal comparisons make little sense. Here we find the following calculations: "On the basis of the known destructive power of various bombs and on the basis of experiments, the bombing survey figured out what bomb load would have been necessary to cause the same destruction in Hiroshima and Nagasaki. In Hiroshima, it would have been necessary to drop 1,300 t of bombs (consisting of one quarter He and three quarters of incendiary bombs) and in Nagasaki it would have been necessary to drop 600 t bombs (three quarters He and one quarter incendiary bombs). Besides, in Hiroshima, 500 t of fragmentation bombs and in Nagasaki 300 t of fragmentation bombs would have been necessary to cause similar human losses. The total bomb load thus would have been as follows: 1,800 t in Hiroshima and 900 t in Nagasaki. If each aircraft carries 10 t, then we would have had to send 180 B-29 bombers against Hiroshima and 90 B-29 bombers against Nagasaki."[17]

The nuclear payload came to about 50 kg both in the Hiroshima bomb (U-235, "gun principle") and in the Nagasaki bomb (Pu-239, implosion principle).

The energy balance shows that, of that amount, about 1 kg were split in each case and that the efficiency thus was 2 percent.

The total weight of each nuclear bomb (including bomb carrier, chute, etc.) was about 5 t. The detonation altitudes were at 600 m or 350 m.

The nuclear armament effort of the United States did not terminate or was not slowed down upon Japan's capitulation and the end of World War II; instead,

it assumed unimaginable proportions. Huge armament industry plants were built and hundreds of thousands of people were employed in them. The United States had a nuclear weapons monopoly and used it as a weapon in the Cold War. With all available means, the United States tried to perfect nuclear weapons and to establish corresponding stockpiles in order to give its policy of strength the necessary emphasis against the Soviet Union. That goal was also served by renewed nuclear weapons tests. The so-called "Abel Bomb" was exploded on 1 July 1946 at an altitude of 500 m between the aircraft carrier "Independence" and a Japanese cruiser as the first surface detonation over water.

The second test followed in the region of Bikini Atoll on 25 July 1946; this was an underwater detonation.

This development was naturally watched very carefully by the Soviet Union. Based on the advantages of the socialist social system, the CPSU and the Soviet government mobilized all available scientific and technical capacities in order to be able to begin with the development, manufacture, and testing of nuclear weapons.

Looking back, A. P. Aleksandrov writes the following on this: "I. V. Kurchatov and the other scientists, engineers, and experts from the most varied fields --who worked on the Soviet atomic project by order of the Central Committee of the CPSU--clearly realized that the development of an equivalent weapon-- even before the United States had gone into the mass production of atomic weapons--was a question of life or death for the defense of the Soviet Union."[18]

In the summer of 1939, the Soviet physicists Ye. B. Zeldovich and Ye. B. Kharitov provided theoretical proof to the effect that the chain reaction of nuclear fission was real and in this way they created certain foundations for the theory of the chain reaction.

In the autumn of 1940, I. V. Kurchatov made a general analysis of the possibilities of bringing about a chain reaction and in the process recognized the enormous difficulties which would stand in the way of practical implementation.

Back in 1939, he had already contacted the Soviet government with a reference on the military problems involved in nuclear fission. The fascist attack on the Soviet Union led to the destruction or evacuation of the laboratories in Kharkov and Leningrad. Moreover, the military situation forced the leading Soviet scientists to devote themselves to the immediate perfection of equipment for the Soviet armed forces.

With the turning point in the Great Fatherland War of the Soviet Union, scientific research then began in the field of uranium fission in 1942. A central study group was created in Moscow in 1943 under the direction of I. V. Kurchatov. The theory of nuclear reactors was developed already in the autumn of 1943 and the first Soviet uranium-graphite experimental reactor became operational on 25 December 1946. In addition to I. V. Kurchatov, the following of his closest collaborators participated in this outstanding event: I. S.

Panayuk, B. G. Dubrovskiy, Ye. N. Babulevich, and A. K. Kondratev. This meant that the "secret" of the production of plutonium, the nuclear explosive, had been discovered.

Parallel to this scientific effort, an efficient nuclear industry was planned and built up. While the imperialist circles in the United States figured on the Soviets getting their first nuclear weapon at the earliest in 1952, the then Soviet Minister Molotov was able to declare already on 6 November 1947 that the United States was no longer the only one to possess the secret of atomic bomb production.[19]

The first Soviet nuclear weapons test detonation took place on 29 August 1949. This meant that the nuclear weapons monopoly of the United States had been broken. The policy of strength had suffered a decisive defeat. But the Soviet Union did not yet have nuclear weapons stockpiles.

On 31 January 1950, Truman signed an order obligating the AEC to make every effort to create a "thermonuclear weapon."[20]

While the detonation equivalents in nuclear fission weapons were still counted in the thousands of tons of TNT, they now grew into the Megaton range. On 1 November 1952, the United States, on Elugelab Island, in the Pacific Ocean, for the first time conducted a test with a thermonuclear device (code name "Mike"). The detonation intensity was 5 Mt and it was thus 250 times greater than that of the Hiroshima bomb.[21] This was a pure test detonation which as yet did not permit any direct military use. The explosive as such weighed about 50 t. The gaseous hydrogen isotopes deuterium and tritium were used as nuclear charge during the synthesis phase.

On 28 February 1954, the United States triggered a second test detonation with an intensity of 15 Mt on Bikini Atoll. This was a transportable device.

On 26 March of the same year, another detonation of similar intensity followed on the Marshall Islands. It may be assumed that lithiumdeuteride (LiD) was used in both cases as nuclear charge.[22]

The enormous speed with which nuclear weapons development continued in the Soviet Union is pointed up by the fact that the first test detonation of a multi-phase nuclear weapon became possible already on 12 August 1953.

According to data from the United States AEC, lithiumdeuteride was used either partly or completely in place of the expensive tritium for nuclear synthesis already during this first experimental detonation. This also explains the fact that the explosive itself was transportable. Other "thermonuclear" test detonations followed in September and October 1954.

On 22 November 1955, the Soviet Union conducted the first air burst of a multi-phase nuclear weapon. The weapon was dropped from an aircraft. All prior thermonuclear detonations in the United States and the USSR until then had been ground bursts.

The first such air burst came off successfully in the United States only on 21 May 1956.[23] These facts show that the Soviet Union was in a position simultaneously to work on the problems of using nuclear fission and nuclear synthesis, finding favorable design solutions quickly, and thus, in the case of multi-phase nuclear weapons, arriving at militarily usable devices faster and creating corresponding stockpiles in shorter periods of time than the United States--all this in spite of the vast losses and damage caused by the fascist attack and more unfavorable economic preconditions.

Even the tremendous efforts of the United States during the following years were unable to change anything on the fact that balance of power was always shifting in favor of the Soviet Union also in the field of nuclear weapons.

In 1953-1957, equality was achieved in nuclear weapons development between the Soviet Union and the United States; during the years thereafter, the Soviet Union gained superiority. On top of that we have the fact that the Soviet Union, parallel to the nuclear warheads, also developed the required delivery vehicles. Thus, TASS [Telegraph Agency of the Soviet Union] on 27 August 1957 reported that the first intercontinental missile had been tested in the Soviet Union. On 4 December 1962, Marshal Biryuzov in the army newspaper KRASNAYA ZVEZDA reported that the Soviet Army had warheads of 50-60 Mt for intercontinental missiles. This meant that even the United States itself was no longer invulnerable.

In recent years the United States again and again tried to make its alleged superiority credible in the field of nuclear weapons. To do that, it used above all the loyal monopoly press to propagate ever new variations of "modern nuclear weapons." Here are some examples.

In 1957 came the so-called "clean bomb," that is to say, a nuclear weapon with less radioactivity (energy release exclusively based on nuclear synthesis); it was touted as being particularly "humane" and served as a pretext for the continuation of American nuclear weapons tests.

Starting in 1959, approximately, American voices were again heard, trying to prove in particular that only the United States, on the basis of "its economic strength," was in a position to produce "smaller nuclear weapons" in adequate quantities.

In 1960, the new "miracle weapon" was the "neutron bomb" which was to work primarily through the neutron component of instant nuclear radiation. In contrast to all the noise about the "clean bomb," it was advertised as being particularly effective precisely because it would act upon man above all through nuclear radiation while the blast wave and the flash [light radiation] would be of subordinate significance in terms of their destructive effect. Here is how the situation was described: "A revolutionary novel nuclear secret weapon has been developed by American scientists according to information supplied by former AEC member Murray. Murray at the same time emphatically came out in favor of lifting the atomic test ban which in effect made it impossible for the United States to win a new position of military and political strength. In the opinion of an American nuclear physicist, who does not wish his name to be known, the new weapon could be a 'neutron bomb' which releases lethal rays without causing any property damage."[24]

Starting in 1961, SAC conducted flights with nuclear bombs on board in the direction toward the Soviet Union and the socialist states. Among the four routes regularly flown, three run from the United States via Canada or Alaska or Greenland and the Polar region while the fourth one extends from the United States across the Middle Atlantic all the way to Spain.

In addition to the potential threat to the entire socialist camp, this kind of action is connected with a direct threat to the countries over which those planes fly. Between 1958 and 1968 alone there were 14 incidents involving nuclear bombs as well as various complications in SAC.

On 17 January 1966, a B-52 exploded during such a flight while refuelling in the air over the Spanish village of Palomares. At that time, three multi-phase nuclear bombs fell on farmland and the fourth one dropped 840 m deep into the Mediterranean.

On 21 January 1968, a B-52 crashed at Thule in the northwestern part of Greanland, hitting the permafrost surface; it exploded and the four nuclear bombs, with an intensity of 1 Mt, each, sank to a depth of 250 m.

Even if one keeps in mind that the multiple safeguard systems practically rule out any unintentional nuclear detonation in this kind of crash, there are still enough danger sources left.

For example, the decomposition of the plutonium fuse due to pressure and heat or the corrosion of the bomb casing cause a radioactive contamination of the terrain or the water. But this directly creates the danger of incorporating the alpha-active plutonium.[25]

England was the third country which, on 3 October 1952, conducted a nuclear fission weapons test on the Monte Bello Islands (northwestern part of Australia). The British nuclear weapons project had been launched in the autumn of 1951 under the code name "Tube Alloys Directorate" under the direction of Wallace Akers. Two other tests followed in 1953 at the Woomera Range in the southern Australian desert. The first test detonation involving a thermonuclear device was carried out on 15 May 1957 in the area of Christmas Island in the Pacific Ocean.

France was the fourth country on 13 February 1960 to detonate its first nuclear fission bomb at Reggane in the Sahara Desert. On 24 August 1968, it set off a thermonuclear device on Fangataufa Atoll in the Pacific Ocean.

Table 1.2. Data on the First "A and H Bomb Test Detonations"[26]

	Staat	»A-Bombe« [2]	Ort [3]	Bemerkungen	»H-Bombe« [2]	Ort [3]	Bemerkungen
	USA	16.07.1945	Alamogordo (New Mexiko) [4]	»Trinity-Test« Pu-239, 10 kt Implosionsprinzip	01.11.1952 [6]	Elugelab (Stiller Ozean)	Test »Mike« D,T; 5 Mt [7] nicht transportabel
			[5]	Stahlturm (30 m)	28.02.1954 [6]	Bikini (Stiller Ozean)	LiD; 15 Mt [8] transportabel
[9]	UdSSR	29.08.1949	[10]	kt-Bereich Pu-239	12.08.1953		[11] Mt-Bereich LiD [8] transportabel
	England	03.10.1952	Monte Bello [12] (Australien)	[10] kt-Bereich	15.05.1957 [13]	Christmas-Insel [6] (Stiller Ozean)	[11] Mt-Bereich
[14]	Frankreich	13.02.1960	Reggane [15] (Wüste Sahara)	60 ... 70 kt [16] Turm (100 m)	24.08.1968	Fangataufa [6] (Stiller Ozean)	2 Mt
[17]	VR China	16.10.1964	[18] Provinz Sinkiang	U-235, 20 kt [16] Turm	17.06.1967	[18] Provinz Sinkiang	3 Mt

Key: 1--Country; 2--Place; 3--Remarks; 4--Implosion principle; 5--Steel tower; 6--Pacific Ocean; 7--Not transportable; 8--Transportable; 9--USSR; 10--Kt range; 11--Mt range; 12--Australia; 13--Christmas Island; 14--France; 15--Sahara Desert; 16--Tower; 17--PRC; 18--Province of Sinkiang.

The PRC was the fifth and, for the time being, last country which on 16 October 1964 announced the first test detonation of a nuclear fission weapon. The test site was in the Province of Sinkiang. A thermonuclear device was exploded at the same site on 17 June 1967.

At this time we must estimate that a series of other imperialist states are working on the manufacture of nuclear weapons, are considering such steps, or are able to do so. Worldwide scientific and technical developments have produced a situation in which today there is practically no more "atomic secret" so that, in the final analysis, only the particular economic strength of a country will decide on the possibility of producing nuclear weapons.

Table 1.2 presents an overview of the first test detonations by the individual countries. In compiling this table and the following one, the problem was that the material available for analysis was not authentic in each case and that conflicting data are available in the literature on various events.

Overall, about 740 nuclear weapons detonations were triggered by the five nuclear powers between 1945 and 1970. We may estimate that this number is too low, rather than too high.

Regardless of this fact, Table 1.3 clearly shows that, even according to Western data, the Soviet Union confined the number of its tests to the militarily possible minimum.

On the basis of available data, we may furthermore estimate that the total equivalent of the detonation energy of all nuclear tests conducted so far is roughly on the order of magnitude of 500-550 Mt TNT.

Of that amount, about 400 Mt were used in about 100 tests in the Mt range in the atmosphere. The remaining 100-150 Mt must be credited to nuclear weapons detonations in the kt range and a few underground detonations in the Mt range. To be able to visualize these orders of magnitude, we may start with the assumption, by way of comparison, that the total intensity of the explosives (bombs, shells, etc.) employed during World War II by all belligerent countries was about 5 Mt.

The tests conducted so far were air, surface, water, and underwater detonations. Here it is particularly difficult to estimate the detonation intensities of underground detonations that were not officially announced. Until the year 1963, the share of underground and underwater detonations out of the total number of tests in the kt range was about 50 percent. Between 1964 and 1970 on the other hand underground detonations alone accounted for more than 90 percent of all tests conducted.

According to Western literature data, the hitherto strongest nuclear weapons detonation with 57 Mt was triggered by the Soviet Union on 30 October 1961 over Novaya Zemlya. The weakest test with a detonation intensity of only 0.0002 took place in Nevada on 30 October 1958. The hitherto highest detonation altitudes would seem to have been selected by the United States during the Argus series in August and September 1958 (three tests at 2 kt, each, at

an altitude of 480 km) and 9 July 1962 with a 1.2-Mt test at an altitude of 320 km over Johnston Island in the Pacific. The hitherto deepest known underground detonation with an intensity of 5 Mt at a depth of 2,000 m was triggered by the United States, in spite of worldwide protests, on 6 November 1971 on the Aleutian island of Amchitka.

Table 1.3. Compilation of Nuclear Weapons Detonations by the Individual Countries, 1945-1970[26]

		1945	1946	1947	1948	1949	1950	1951
	USA	3	2	–	3	–	–	17
	UdSSR	–	–	–	–	1	–	2
1	Insgesamt:	3	2	–	3	1	–	19

		1952	1953	1954	1955	1956	1957	1958
	USA	9	11	6	15	14	28	66
	UdSSR	–	2	1	4	7	13	25
	England	1	2	–	–	6	7	5
1	Insgesamt:	10	15	7	19	27	48	96

		1959	1960	1961	1962	1963	1964	1965
	USA	–	–	8	87	46	29	27
	UdSSR	–	–	30	38	3	5	8
	England	–	–	–	2	–	–	1
2	Frankreich	–	3	1	1	1	1	–
3	VR China	–	–	–	–	–	1	1
1	Insgesamt:	–	3	39	128	50	36	37

		1966	1967	1968	1969	1970	1945–1970
	USA	9	33	32	27	27	499
	UdSSR	2	8	7	12	9	177
	England	–	–	–	–	–	24
2	Frankreich	5	4	5	–	8	29
3	VR China	3	2	1	2	1	11
1	Insgesamt:	19	47	45	41	45	740

Key: 1--Total; 2--France; 3--PRC; UdSS--USSR.

Figure 1.6. Geographic location of the most important nuclear weapons test sites of the United States, England, France, and the PRC.
Explanation for Figure 1.6

United States test sites: Nevada, U.S.A. (1), New Mexico, U.S.A. (2), Johnston Islands, south of Hawaii, Pacific Ocean (3), Bikini (Island), Marshall Islands, Pacific Ocean (4), Eniwetok (Island), Marshall Islands, Pacific Ocean (4), Amchitka (Island), Aleutians (5).

England's test sites: Woomera, southern Australia (6), Monte Bello (Islands), off the northwest coast of Australia (7), Christmas Island, Gilbert and Ellice Islands, Pacific Ocean (8).

France's test sites: Reggane, Central Sahara (9), Muruoa (Island), French Polynesia, Pacific Ocean (10), Fangataufa (Island), French Polynesia, Pacific Ocean (10).

PRC test sites: Province of Sinkiang, northwestern part of China (11).

Between 1945 and today we have two phases during which there were no nuclear weapons tests or during which these tests were or still are subjected to certain restrictions.

The first relative test suspension period, which was not based on any treaty agreement, lasted from the autumn of 1959 until September 1961. During that span of time, only France conducted nuclear weapons tests.

The second relative period of test suspensions began on 5 August 1963. On that date, the foreign ministers of the Soviet Union, the United States, and Great Britain signed the "Agreement on the Suspension of Nuclear Weapons Tests in the Atmosphere, in Outer Space, and Under Water" in Moscow. This step restricted the increasing "radioactive pollution" of the earth's atmosphere and the ocean water--but it only restricted it because France and the PRC did not sign that agreement. Another important step toward a reduction in international tensions was taken in 1968. After many years of constructive proposals by the Soviet Union and its efforts to achieve visible results in disarmament negotiations,

a proposal, submitted by the Soviet Union, was signed on 18 January 1968; the "Draft for a Treaty on the Nontransfer of Nuclear Weapons" was signed in Geneva by the 18-member disarmament committee of the UN.

The United States had submitted an identical treaty draft. On that basis, the 22nd UN General Assembly with an overwhelming majority on 12 June 1968 passed the nuclear weapons ban treaty which finally on 5 March 1970 entered into force after having been signed by more than a hundred countries, including of course the GDR. This created obligations which were binding under international law, obligations to refrain from any further dissemination of nuclear weapons and to stop the efforts of non-nuclear countries to gain access to nuclear weapons in any form whatsoever.

Negotiations then began in 1969 between the Soviet Union and the United States concerning the use of nuclear detonations for peaceful purposes; these negotiations are still going on as we prepare this chapter (August 1971).

The past history of nuclear weapons sketched here briefly, also confirms the observation of the International Conference of the Communist and Worker Parties of August 1969 in Moscow: "In view of the existing international balance of power, the nuclear weapons potential of the Soviet Union, and the possible consequences of a nuclear missile war, it is becoming increasingly difficult and dangerous for United States imperialism to bank on unleashing a new world war. Under these conditions, ruling American circles place special emphasis on local wars without abandoning the preparations for a world war. But the contrast between the policy of strength pursued by imperialism and its real possibilities is emerging ever more crassly."[27]

Review Questions

1.6. Into what fundamental stages can the past history of nuclear weapons be broken down?

1.7. Explain why the rapid development of Soviet nuclear weapons "was a matter of life and death for the defense of the Soviet Union."

1.8. What are the causes for the fact that the Soviet Union was able quickly to break the American nuclear weapons monopoly and then to achieve and maintain a lead in the development of nuclear missiles?

1.9. What international and military significance is attached to the Agreement on the Suspension of Nuclear Weapons Tests in the Atmosphere, in Outer Space, and Under Water, dated 5 August 1963, and the entry into force of the Nuclear Nonproliferation Treaty, dated 5 March 1970?

1.10. What is the connection between the need for constantly increasing the combat readiness of the NVA [National People's Army] and the struggle of the socialist countries, headed by the Soviet Union, for disarmament and a general ban on the use of nuclear weapons and other mass annihilation weapons?

1.3. Structure of Nuclear Fission Weapons

1.3.1. Nuclear Fission as Basis of Energy Release

1.3.1.1. Mass Defect and Nuclear Binding Energy[28]

Three types of elementary particles are involved in the immediate build-up of the atoms: Electrons, protons, and neutrons.

The atom itself consists of a relatively loose envelope of electrons and a very small nucleus with an extraordinarily high mass and charge density. The outside diameter of an atom is on the order of magnitude of 10^{-10} m, that of the nucleus is only 10^{-15} m. More than 99.9 percent of the total mass [weight] of an atom are concentrated in the nucleus. This means that the nucleus has a mass density of about 10^{17} kg m^{-3}.

Concerning the problems of nuclear energy release, we are only interested in the atomic nucleus. The energy amounts which can be released by changes in the nuclear structure can be 10^6 times higher than in chemical reactions.

In keeping with the theory of relativity, a particle also still has energy if its velocity is zero. This energy is called rest energy. The following relation then applies:

$$E = m \cdot c^2 \qquad (1.1)$$

It expresses the equivalence of energy and rest mass of a particle and, during the release of nuclear energy, supplies the connection between nuclear binding energy and mass defect. If, for example, we mathematically determine, from the individual masses, the mass of a helium atom (^4_2He; $2e^-$) on the basis of the values in Table 1.4 with the help of the following formula

$$m_A = Z \cdot m_p + N \cdot m_n + Z \cdot m_e \qquad (1.2)$$

Then, using the relative atomic weights, we get a value of $m_{He} = 4.0329$ ME. Compared to the real atomic weight of helium (m = 4.0026 ME), this value turns out to be 0.0303 ME too high.

Table 1.4. Brief Characteristics of Elementary Particles: Electron, Proton, and Neutron

1	Elementarteilchen	Elektron	Proton	Neutron
	Symbol	e^-	p	n
2	Ruhemasse, absolute kg	$9{,}1091 \cdot 10^{-31}$	$1{,}6725 \cdot 10^{-27}$	$1{,}6748 \cdot 10^{-27}$
3	Ruhemasse, relative ME[1]	0,000549	1,00727	1,00865
4	Ruhemasse, äquv. MeV/c^2	0,5110	938,3	939,5
5	Elementarladung	−1	+1	0
6	mittlere freie Lebensdauer s	stabil 7	stabil 7	$1{,}0 \cdot 10^3$

Key: 1--Elementary particle; 2--Rest mass, absolute; 3--Rest mass, relative; 4--Rest mass, equivalent; 5--Elementary charge; 6--Average free lifetime; 7--Stable; (1) The relative atomic mass (rest mass) must not be confused with the mass number (mass number = proton number + neutron number); A = Z + N). Since 1961, the atomic mass unit has been defined as follows: 1 ME = 1/12 atomic mass of $^{12}_{6}C$ = $1.66043 \cdot 10^{-27}$ kg. The relative atomic mass accordingly is the ratio between the atomic mass of the corresponding atom (particle) and the atomic mass unit.

By way of explanation we might say that, during the formation of an atomic nucleus from free nucleons (protons and neutrons)--there develops a mass defect in whose place there comes an energy quantity which is equivalent according to Formula 1.1.

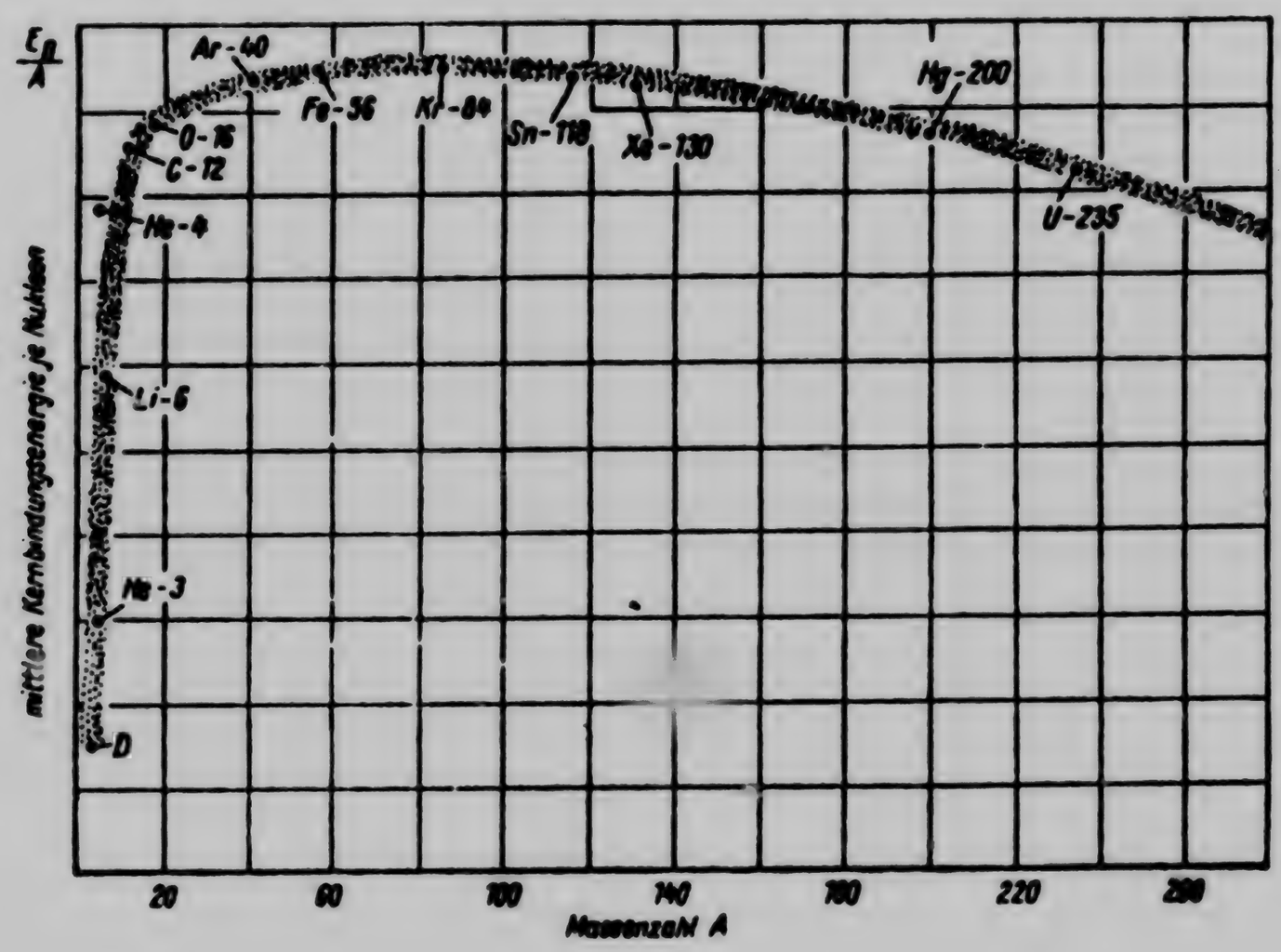
If we wanted to reverse this process, this energy would precisely once again have to be used for the separation of the nucleons. Looking at it this way nuclear energy is, by virtue of its essence, nuclear binding energy. Or, in other words, the more firmly a nucleon is bound to a nucleus as a result of a nuclear reaction, the greater will be the attendant mass defect and thus the released equivalent energy quantity.

The reciprocal processes between atomic nuclei of varying structure or between those with different nuclear-active particles is considerably more complicated than the above example of the buildup of an atom or atomic nucleus from elementary particles. Such nuclear reactions can reveal both a positive and a negative energy balance. Basically, nuclear energy is released only if the mass of the nuclei or nuclear particles participating in the reaction meet the following inequality:

$$\Sigma m_{\text{original [parent] nuclei}} > \Sigma m_{\text{product}} \qquad (1.3)$$

We get initial conclusions as to the anticipated energy toning of a nuclear reaction if we illustrate the nuclear binding energy per nucleon as a function of the mass number; that is to say, in other words, if we divide the binding energy of any desired nucleus by the number of nucleons forming that nucleus.

In this case we can recognize that, up to a mass number of A = 60, the average nuclear binding energy per nucleon grows rapidly in terms of tendency and then again slowly decreases in the direction toward the heavy nuclei. Thus the average binding energy per nucleon is about 7 MeV for helium, 9 MeV (maximum) for iron, and 7.5 MeV for uranium; for the total spectrum of atomic nuclei, the value on the average is 8 Mev; this corresponds to a mass defect of 0.0089 ME. Nevertheless, especially in some light nuclei, there are considerable deviations from these average values. We can furthermore observe that the binding energy per nucleon for nuclei with an even mass number is greater than for the neighboring nuclei with an uneven mass number.



1

2

Figure 1.7. Average nuclear binding energy per nucleon as function of mass number A[29]. Key: 1--Average nuclear binding energy per nucleon; 2--Mass number A.

By way of summary, from what we have said here so far, we can derive two possibilities of nuclear energy procurement which were formulated already in Section 1.1., that is, the buildup of heavy nuclei from light nuclei and the fission of heavy nuclei into medium ones.

To continue our look at energy release based on nuclear fission (nuclear synthesis) it is not enough to illustrate the nuclear binding energy simply as a function of the mass number A because the latter after all consists of Z and N. Concerning the stability of a nucleus, the breakdown according to even or

odd proton and neutron numbers ((g, g)-, (g, u)-, (u, g)-, (u, u)- nuclei) provides further insight. It thus turns out that, in nature, nuclei of type (g, g) predominate (164 stable nuclides) while only four stable nuclides are known of nucleus type (u, u). In general we can say that the stability of the individual nucleus types decreases in the sequence mentioned above.

The stability of atomic nuclei is essentially determined by the number and the mixing ratio of protons and neutrons. For stable nuclei, we have $N = Z$, whereas for heavy nuclei we must have $N > Z$. Starting $Z \geq 84$ (Polonium), we only have unstable nuclides.

In the atomic nuclei which are made up of protons (positive elementary charge) and neutrons (no electrical charge), there must be different forces present which, in their totality, determine its stability or instability. In simplified form, this interconnection can be boiled down to the opposing action of the nuclear forces and the Coulomb forces.

Experience shows that there are strong binding forces also between the protons or neutrons among each other and between protons and neutrons as such. The magnitude of the binding forces decreases very rapidly as the distance increases; their practical range does not exceed $2 \cdot 10^{-15}$ m. These nuclear forces cause the formation of the nucleus from the nucleons. The nuclear forces act only between neighboring nucleons. This shows us that the "surface nucleons," which after all do not have any external neighbors, are bound more weakly than those deep in the nucleus. This assumption furthermore yields a certain surface tension and the explanation for the fact that most nuclei have a roughly spherical shape ("dr.plet model" or the atomic nucleus).

The nature of nuclear forces is still not fully understood. According to H. Yukawa, nuclear forces--similar to chemical binding forces--are considered exchange forces between the nucleons. The π-mesons or pions are considered as carriers of the nuclear force field. They can be exchanged between the nucleons.

The Coulomb forces, which work against the nuclear forces, result from the repelling effect of protons with the same charge. In comparison to them, they have a considerably greater range. Their magnitude decreases with the square of the distance between the protons. This is why each of the Z-protons acts upon the other (Z-1) protons.

While the nuclear forces increase only in proportion to Z, the Coulomb forces increase at Z^2. Because of the change in the ratio between protons and neutrons from 1:1 to about 1: 1.6--a change extending from the light to the heavy atomic nuclei--there is an increase in the average distance between the protons; but that cannot prevent the fact that, in the end, in case of very high nuclear charge numbers, the Coulomb forces will prevail which means that the nucleus becomes unstable. An atomic nucleus thus is stable so long as the following condition is met:

$$\Sigma F_{\text{nuclear forces}} > \Sigma F_{\text{Coulomb forces}} \qquad (1.4)$$

According to Bohr, the folowing inequality applies here:

$$\frac{Z^2}{A} < 45 \quad \text{or} \quad \frac{Z^2}{Z+N} < 45 \tag{1.5}$$

1.3.1.2. Basic Condition for Nuclear Fission

Nuclear fission reactions can basically be triggered in a whole series of nucleus types. But only a certain number of heavy nuclei is suitable for use as fission materials (nuclear explosives). As far as we know now, for nuclear fission weapons, that would be the nuclides U-233, U-235, Pu-239, and possibly also Cf-249 and Cf-251. The nuclides U-238 and (Th-232) can furthermore be considered for use in multi-phase nuclear weapons.

The nuclei of these radionuclides are subjected to spontaneous nucleus decay or alpha decay. Compared to the half-life for the spontaneous nuclear decay ($T_s = 1.8 \cdot 10^{17}$ a for U-235) with those of alpha decay ($T_\alpha = 7.1 \cdot 10^{8}$ a for U-235) however shows that spontaneous fission is only very rare. From this we can also without further consideration draw the conclusion that a certain activation energy must be used in order to bring about forced nuclear fission. Its magnitude for nuclei with a mass number of A ~ 230 is less than 10 MeV.

The required activation energy can be supplied to the nucleus to be split by means of photons or due to the impact of particles (kinetic energy) and/or by their absorption (formation of an intermediate nucleus--binding energy). In the case of nuclear fission weapons, the neutrons are the sources of this activation energy.

The basic condition for nuclear fission in nuclear weapons consists in the fact that the sum of the binding energy E_B of the neutron absorbed in the intermediate nucleus and its kinetic energy E_{kin} is equal to or greater than the required activation energy E_w for the nuclide used as nuclear charge.

The following applies as a prerequisite for nuclear fission by means of neutrons:

$$E_{B(n)} + E_{kin(n)} \geq E_w \tag{1.6}$$

Table 1.5 shows the activation energies for the most important nuclear explosives. We can see that, in the case of U-235 and Pu-239, the bonding energy of the neutron corresponds to the necessary activation energy or exceeds it. Something similar applies to U-233 which is not listed in the table. This is why these nuclides can already be split by thermal neutrons. (Thermal neutrons at 25° C have an average energy of $\bar{E}_n = 0.025$ MeV, at an average velocity of $v = 2.2 \cdot 10^{3}$ m s^{-1}.) On the other hand, fast neutrons with an energy of $E_n \geq 1.5$ MeV are necessary for splitting U-238 (Th-232).

Table 1.5. Activation Energy E_w (Neutrons) in Terms of MeV for Some Heavy Nuclei[30]

Original nucleus	U-235	U-238	Pu-239
Intermediate nucleus	U-236	U-239	Pu-240
Activation energy	6.5	7.0	5.1
Neutron's binding energy	6.8	5.5	5.1
Neutron's kinetic energy	0	1.5	0

This difference exerts decisive influence on the possibilities of using both of these groups of nuclear explosives. We will go into greater detail on that later on.

With the help of the droplet model for the atomic nucleus it is possible clearly to illustrate the nuclear fission process. The supply of activation energy--which is connected with the absorption of the neutron and the formation of the intermediate nucleus--excites the fissile nucleus into pulsating oscillations. As a result of these oscillations, the previously spherical nucleus is deformed and it assumes a longitudinal, dumbbell-like shape. Two, spatially separated positive charging foci now begin to form, the Coulomb forces gain the upper hand, and finally lead to the splitting of the nucleus into two fragments (nuclear fragments). At the same time, two or three neutrons are released during this process. This is connected with the release of an energy amount that is equivalent to the developing mass defect and whose carriers [sources] are the nuclear fragments which move away from each other at fast speed, the neutrons, and the immediately emitted nuclear radiation (see Section 1.3.4.).

To conclude these elementary considerations, we might note that, even under the conditions given, not every absorption of a neutron need necessarily lead to nuclear fission. Instead, nuclear fission, like any other nuclear reaction, takes place only with a certain probability. Thus, we can match nuclear fission with a certain "action profile" which specifically depends on the nuclear structure and the energy of the neutrons.

If we look at the example illustrated in Figure 1.8, we find the following reaction probabilities:

During the absorption of thermal neutrons by U-235 nuclei, the probability of nuclear fission is 85 percent; in 13 percent of the cases, we get, on the average, neutron capture with the emission of a γ-quantum ((n, γ)-reaction) and in 2 percent of the cases we get elastic scatter ((n, n')-reaction).

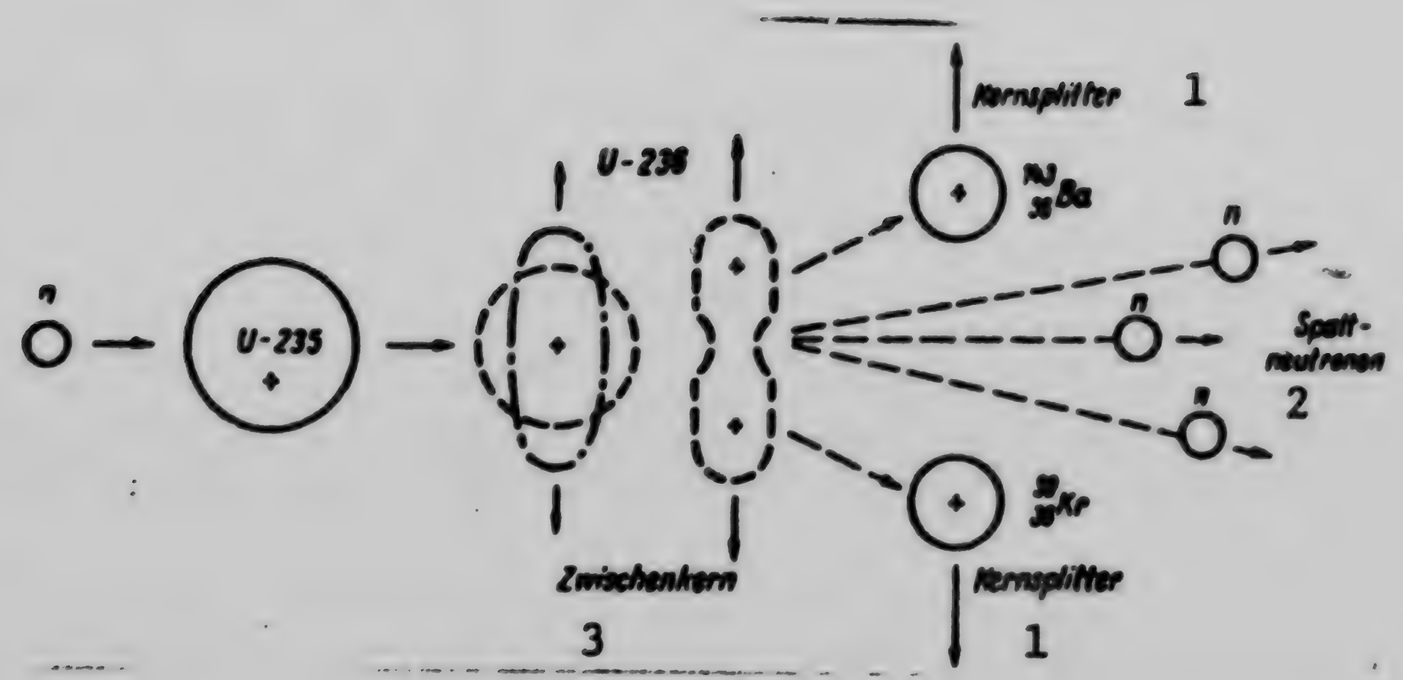


Figure 1.8. Basic diagram illustrating forces nuclear fission through neutron bombardment. Key: 1--Nuclear fragments; 2--Fission neutrons; 3--Intermediate [compound] nucleus.

1.3.1.3. Chain Reaction in Nuclear Explosive

The fission of the nuclear explosives mentioned is accompanied by four common characteristics:

For each nucleus split, we get an energy amount on the order of magnitude of about 200 MeV;

Two or three neutrons per fission event are released;

At the moment of fission, an average of 2 gamma quantums are emitted;

The nuclear fragments of the uranium or plutonium nucleus--the fission products--developing as a result of fission are radioactive.

The characteristic mentioned in second place--according to which secondary neutrons develop during nuclear fission--is particularly important. If the binding energy of these fission neutrons is enough in order, in turn, to bring about more nuclear fission, then a fission process, which has been initiated, can under certain conditions continue by itself and lead to a so-called chain reaction. This as we know applies to the nuclides U-233, U-235, and Pu-239.

The possibility of more nuclear fission due to secondary fission neutrons however does not yet lead to the development of such a chain reaction whose result is the release of nuclear energy through a detonation. For that, a series of other conditions must be met, that is to say, first of all, the chain reaction must continue via a number of fission cycles that will release enough energy and, besides, energy release must take place within a sufficiently short time interval.

The term "chain reaction" in the case of nuclear weapons means a series of exoergenic nuclear reactions which, after external initiation, will continue by themselves and which--due to the number of fission neutrons that keeps growing from generation to generation, from fission cycle to fission cycle--will

encompass more and more nuclei, will grow like an avalanche, and will thus release large quantities of energy within fractions of seconds in the form of a detonation.

As a basic prerequisite for the detonation-like release of nuclear energy, it emerges from the definition given that the number of fission neutrons must grow from generation to generation; that is to say, that the neutron multiplication factor k must be greater than unity.

The neutron multiplication factor k is defined as the quotient of the i/i-1 neutron generation.

A system, for which k < 1 applies, is termed subcritical. A reaction initiated from the outside will quickly die down again. When k = 1, a system is critical. The reaction takes place at steady speed and the energy release takes place in proportion to the reaction time (reactor).

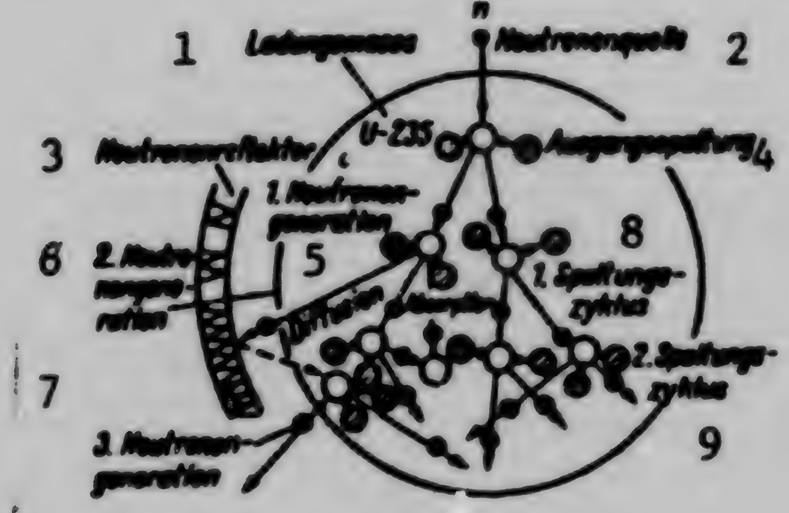


Figure 1.9. Basic diagram illustrating the course of the chain reaction in nuclear fission weapons. Key: 1--Charge mass; 2--Neutron source; 3--Neutron reflector; 4--Initial fission; 5--1st neutron generation; 6--2nd neutron generation; 7--3rd neutron generation; 8--1st fission cycle; 9--2nd fission cycle.

At the moment of ignition, k > 1 applies to the nuclear weapon.. It must then be considered a supercritical system.

$$k = \frac{i}{i-1} > 1 \qquad (1.7)$$

Under specific conditions, the magnitude of the multiplication factor k depends on the number of neutrons released per fission event, the ratio between the nuclear fission cross-section and the cross-section for other processes not leading to the release of new neutrons, the type, size, and shape of the particular fission material, as well as some other marginal conditions.

If all of the neutrons released during nuclear fission were to cause further fission, then the neutron multiplication factor could attain a maximum value of about k = 2.5. This value however cannot be achieved in nuclear weapons. The

most important reasons for this are that a part of the neutrons is diffused out of the nuclear fission zone while another part is absorbed by the fission product, the admixtures, etc.

Basically we must observe that the course of a chain reaction is always tied to a minimum quantity of nuclear explosives.

To bring about a chain reaction when $k > 1$, we need a certain quantity of fission material. This minimum quantity is called the critical mass.

The critical mass is not a fixed absolute magnitude. Instead, it depends both on the nuclear-physics parameters of the particular nuclear explosive and on the design and structure of the nuclear weapon itself. If we start with a spherical charge arrangement, then the size of the critical mass is determined by the effect cross-section, the neutron multiplication factor, and the average free path length of the neutrons. The action cross-section however depends on the velocity (energy) of the fission neutrons. The free path length of the neutrons again is determined by the nuclear fission cross-section and the number of fissile nuclei per charge mass volume unit. This is why the diameter of the nuclear charge in the supercritical state must be considerably larger than the average free path length of the neutron. Further comments on this problem complex can be found in the following chapter.

1.3.2. Basic Elements of Nuclear Fission Weapons

The basic elements of each nuclear fission weapon are the nuclear charge, the detonation device, and the casing.

Without going into detail, we will explain its essential structure and basic function below.

1.3.2.1. Nuclear Charge

The most important characteristic magnitudes for the nuclear charge are the nuclear explosive used, the charge mass, and the charge volume. The tables below present some values in this connection.

Table 1.6. Brief Description of Nuclear Explosives

1	Nuklid	$^{233}_{92}U$	$^{235}_{92}U$	$^{239}_{94}Pu$
2	Kernmasse, absolute kg	$3{,}8694 \cdot 10^{-25}$	$3{,}9027 \cdot 10^{-25}$	$3{,}9693 \cdot 10^{-25}$
3	Kernmasse, relative ME	233,03784	235,04232	239,05053
4	kritische Masse kg[1])	7,5	22,8	5,6
5	Spaltneutronen je Kern	2,5	2,4	2,9
6	Dichte g cm^{-3}	18,7	19,0	19,6
7	T, Alphazerfall a	$1{,}6 \cdot 10^{5}$	$7{,}1 \cdot 10^{8}$	$2{,}4 \cdot 10^{4}$
8	T, spontane Spaltung a	$3{,}0 \cdot 10^{17}$	$1{,}8 \cdot 10^{17}$	$5{,}5 \cdot 10^{15}$
9	rel. Häufigkeit des Isotops bzw. Brutstoff	Th-232[2])	0,71 %	U-238[3])

Key: 1--Nuclide; 2--Nuclear mass, absolute; 3--Nuclear mass, relative; 4--Critical mass; 5--Fission neutrons per nucleus; 6--Density; 7--T, alpha decay; 8--T, spontaneous fission; 9--Relative frequency of isotope or breeder substance.

(1) The data pertain to a system made up of metallic U-233, U-235, or Pu-239 with a standard water reflector. For nuclear fission weapons, the values are considerably lower.

(2) The production of U-233 takes place in breeder reactors from Th-232 according to the following scheme:

$$^{232}_{90}Th\,(n,\gamma)\,^{233}_{90}Th \xrightarrow[\beta^-]{23{,}5\ min} {}^{233}_{91}Pa \xrightarrow[\beta^-]{27{,}4\ d} {}^{233}_{92}U$$

(3) The production of Th-239 from U-238 is based on the following scheme:

$$^{238}_{92}U\,(n,\gamma)\,^{239}_{92}U \xrightarrow[\beta^-]{2{,}3\ d} {}^{239}_{93}Np \xrightarrow[\beta^-]{23\ min} {}^{239}_{94}Pu$$

The detonation energy of 1 kg TNT corresponds roughly to an energy amount of 1,000 kcal. If we therefore insert q in terms of kt in the following expressio for the detonation equivalent of a nuclear fission weapon, then we get the following for the total energy released as a function of the detonation intensity:

$$E_{Spr} = 10^6 \cdot q \quad \text{kcal} \qquad (1.8)$$

Considering the corresponding conversion factors for the energy units, it therefore follows furthermore that:

$$E_{Det} = 4{,}187 \cdot 10^{19} \cdot q \quad \text{erg} \tag{1.9}$$

and

$$E_{Det} = 2{,}614 \cdot 10^{25} \cdot q \quad \text{MeV} \tag{1.10}$$

Assuming that an energy amount of 200 MeV is released per nucleus split, we can compute, from the numerical value Equation 1.10, the number of nuclear fission acts z necessary to release the detonation intensity q as follows:

$$z = \frac{E_{Det}}{E_{sp}} = \frac{2{,}614 \cdot 10^{25} \cdot q}{200}$$

$$z = 1{,}307 \cdot 10^{23} \cdot q \text{ nuclei.} \tag{1.11}$$

By inserting the Avogadro constant N_A into this equation ($N_A = 6.02252 \cdot 10^{26}$ $1/(A\ kg)$)[31], it follows, for the size of the necessary charge mass Q' in kg, if the minor differences in the sizes of the kg atoms A kg of U-233, U-235, or Pu-239 are neglected, that:

$$Q' = \frac{z}{N_A} = \frac{1{,}307 \cdot 10^{23} \cdot q}{\frac{6{,}023 \cdot 10^{26}}{235}} = \frac{1{,}307 \cdot 10^{23} \cdot q \cdot 235}{6{,}023 \cdot 10^{26}}$$

$$Q' \approx 0{,}05 \cdot q \quad \text{kg} \tag{1.12}$$

The complete fission of the nuclei of about 500 g of the particular nuclear explosive is thus necessary to release the detonation energy of 1 kt TNT.

Assuming that the nuclear fission of the charge mass of a nuclear weapon always takes place only at a certain efficiency η, the practical mass Q of the nuclear charge must always be considerably larger than Q'. The following then applies as a function of η:

$$Q \approx \frac{0{,}05 \cdot q}{\eta} \quad \text{kg} \tag{1.12}$$

From this it follows for the magnitude of the particular charge volume V_L that:

$$V_L = \frac{Q}{\varrho} \cdot 10^3 \quad \text{cm}^3 \qquad \left|\frac{Q}{\text{kg}}\right| \left|\frac{\varrho}{\text{g cm}^{-3}}\right| \tag{1.13}$$

The values for the density ρ can be seen in Table 1.6.

Regardless of the fact that the size of the nuclear charge of a nuclear fission weapon must correspond to the particular detonation intensity, it must in every

case be greater than the critical mass of the nuclear explosive used. A detonation is impossible under other conditions.

Table 1.7. Reference Values for Important Characteristic Magnitudes of Nuclear Fission Weapons(1)

1 Detonationsstärke	5 kt	10 kt	20 kt	50 kt	100 kt
q/kcal	$5 \cdot 10^9$	10^{10}	$2 \cdot 10^{10}$	$3 \cdot 10^{10}$	10^{11}
q/MeV	$1{,}3 \cdot 10^{26}$	$2{,}6 \cdot 10^{26}$	$5{,}2 \cdot 10^{26}$	$1{,}3 \cdot 10^{27}$	$2{,}6 \cdot 10^{27}$
Q/kg	1,25	2,5	5,0	12,5	25
V_L/cm³	65	130	260	650	1300
r_L/cm	2,5	3,1	4,0	5,4	6,8

Key: 1—Detonation intensity; (1) The data in this table were calculated with the help of the formulas given above, assuming an efficiency of $\eta = 0.2$ of nuclear fission. The value r_L in the last line gives us the theoretical radius of the supercritical charge arrangement.

On the basis of the nuclear physics considerations presented in Section 1.3.1.3 concerning the critical mass we can say by way of generalization that its particular specific size depends on the following:

The type of nuclear explosive,

The shape of the nuclear charge,

The density of the nuclear explosive,

Its purity, as well as,

The construction of the detonation mechanism and the casing.

Other things being equal, the smallest critical mass undoubtedly is attained through a spherical arrangement of the fission material because we then get the best ratio between the volume and the surface of the nuclear charge.

The larger the surface of the active zone in relation to the charge mass, the bigger will be the neutron losses due to diffusion. If therefore the charge volume in terms of its shape deviates heavily from that of a sphere, then the size of the critical mass increases greatly and the neutron losses finally become so heavy that, regardless of the quantity of available nuclear explosive, a detonation becomes impossible. If we have a cylindrical nuclear charge of Pu-239, that, for example, will be the case if the radius of the cylinder is smaller than 2.15 cm (prerequisites same as in Table 1.6).[32] In the combination of subcritical charge parts to make up a supercritical overall system, the ratio between the volume and the surface of the nuclear charge is also changed

necessarily. For example, if, in a certain design of a nuclear fission weapon, we have 10 kg U-235 in the shape of two separate spheres, then their surface is about 240 cm^2, each; after their combination, the total surface on the other hand is only about 310 cm^2.

Changes in the density of the nuclear explosive likewise lead to an immediate change in the overall system's critical parameters. The book entitled "Kerndetonationen" [Nuclear Detonations] already points out that, in the nuclear fission bomb dropped on Nagasaki, by the United States, the critical mass was brought about by means of an implosion.[33] Here, a thin-walled hollow sphere made of Pu-239 was reportedly surrounded by an explosive mantle whose detonation energy upon ignition brought about the supercritical state due to the deformation and compression of the plutonium charge.

Assuming that the density of the nuclear charge and the density of the reflector change in proportion--the function of the neutron reflector will be covered later on--we can say that an increase in the density by the factor a brings about a reduction of the linear dimensions of the critical mass by 1/a, of the corresponding volume by $1/a^3$, and of the critical mass itself by $1/a^2$.

In other words, this means that the magnitude of the critical mass is inversely proportional to the square of the density. At a pressure of 1 million kp cm^{-2}, the density of the nuclear charge would thus be doubled while the size of the critical mass would still be 1/4 of the initial value.

The purity of a nuclear explosive also exerts essential influence on the magnitude of the critical mass. Here, the particular share of foreign atoms depends especially on the specific production methods (separation methods) used for the fission materials and this must also be considered from economic viewpoints.

For example, a nuclear charge of U-235 will always contain a certain percentage of U-238. U-238 however can be considered an absorber for thermal neutrons. Depending upon the share of foreign isotopes, the fission neutrons thus are subjected either to fission capture or to radiation capture (n, γ). These absorbed neutrons do not participate in the further chain reaction. This causes a deterioration in the neutron multiplication factor and the size of the required critical mass will necessarily increase.

The situation is similar in the case of U-233 and Pu-239. The fission products as well as other construction materials used in the nuclear weapon can also act as neutron absorbers. The problem complex of the neutron reflector and its decisive significance to the size of the critical mass and the efficiency of nuclear explosive utilization will be discussed in connection with the description of the function of the casing of a nuclear fission weapon in Section 1.3.2.3. At this point we might merely remark that, in the case of nuclear fission weapons, it is possible, due to a corresponding construction of the actual reaction compartment, again to throw a part of the neutrons coming out of the active zone back into it and thus to influence the neutron multiplication factor.

1.3.2.2. Detonation Device

The detonation device of a nuclear weapon comprises the ignition mechanism, including the safety system, devices for the fast materialization of the supercritical charge arrangement, as well as additional elements which are necessary for the materialization of the chain reaction and (as a rule) for the maximum utilization of the nuclear charge; in other words, a high efficiency.

The ignition process essentially contains the removal of the last safety device after separation from the delivery means or, upon reaching the target area, the ignition of the initial explosive, the combination of the individual charge parts or the production, elsewhere, of the supercritical mass and the triggering of the chain reaction. Ignition, for example, can be triggered by impact fuses, time fuses, air-pressure fuses (built-in barometer), proximity fuses (radar fuses), or also influence fuses (using the heat radiation or magnetic field influencing of the target). Until the moment of ignition, the nuclear charge is in the subcritical state and is secured several times over and independently of the other components against unintentional detonation.

Considering the mentioned factors which determine or essentially influence the size of the critical mass in a specific charge arrangement, we get several ways to bring about the supercritical state of the nuclear charge and thus to trigger the internal detonation process.

The first basic way consists in the fact that the total charge is so broken down into charge components and placed in the weapon that the mass of each component charge is smaller than the critical mass of the nuclear explosive. But this means that the number of necessary component charges keeps growing as the detonation intensity increases. This cannot be done in an unlimited fashion for certain reasons. If, for example, the size of the critical charge for U-235 increases to about 6 kg (with reflector), then it would be necessary to subdivide the nuclear charge of a nuclear fission weapon with a detonation intensity of q = 100 kt into more than four parts. The biggest difficulty now obviously would not be this subdivision process but rather the simultaneous combination--coordinated to 1/1,000,000 sec, of the individual charge parts to make up the supercritical overall arrangement. If there is even the slightest delay in a charge part, this produces severe effects on the entire course of the detonation and the magnitude of the released detonation energy. This is why one may assume that this principle is used only in conjunction with small detonation intensities.

The second basic way consists in the fact that the supercritical charge mass is brought about as a result of an implosion. In this case, the entire nuclear charge is placed in the weapon in a compact fashion so that there are no mobile individual charge parts. The overall charge nevertheless is in the subcritical state and this is due to the fact that the nuclear explosive is arranged in the shape of a thin-walled sphere or is present as a loose, highly porous material. The nuclear charge itself is surrounded by a neutron reflector which, in turn, again is surrounded all over by the initial explosive. At the moment of ignition, the reflector and the nuclear charge are compressed extremely powerfully and as a result of that the total system becomes supercritical and the nuclear weapon explodes.

In addition to these possibilities of switching the nuclear weapon from the subcritical to the supercritical state mentioned here, others are conceivable which however are of minor significance in understanding the overall problem complex and which therefore will not be further described here.

A decisive prerequisite for a high degree of nuclear explosive utilization among other things consists in the fact that, at the moment of ignition, the supercritical charge state is in fact brought about instantly and that the process of energy release takes place in the shortest possible time interval.

This simply springs from the fact that the weapon is broken down very quickly as a result of the detonation although about 90 percent of the total detonation energy comes only from the last fission cycle of the chain reaction.

Table 1.8 presents an overview of the number of fission cycles n, the total duration of the course of the chain reaction t, as well as the time span t_1 during which about 90 percent of the detonation energy are released. The data in the table were calculated for a multiplication factor of k = 2 and an average time duration of 10^{-8} sec between two fission events.

Table 1.8. Reference Values to Describe the Course of the Chain Reaction

1 Detonationsstärke	5 kt	10 kt	20 kt	50 kt	100 kt
n	79	80	81	83	84
t/s	$7{,}9 \cdot 10^{-7}$	$8{,}0 \cdot 10^{-7}$	$8{,}1 \cdot 10^{-7}$	$8{,}3 \cdot 10^{-7}$	$8{,}4 \cdot 10^{-7}$
t_1/s	$5{,}1 \cdot 10^{-8}$	$6{,}5 \cdot 10^{-8}$	$8{,}1 \cdot 10^{-8}$	$1{,}1 \cdot 10^{-7}$	$1{,}4 \cdot 10^{-7}$

1. Key: 1—Detonation intensity.

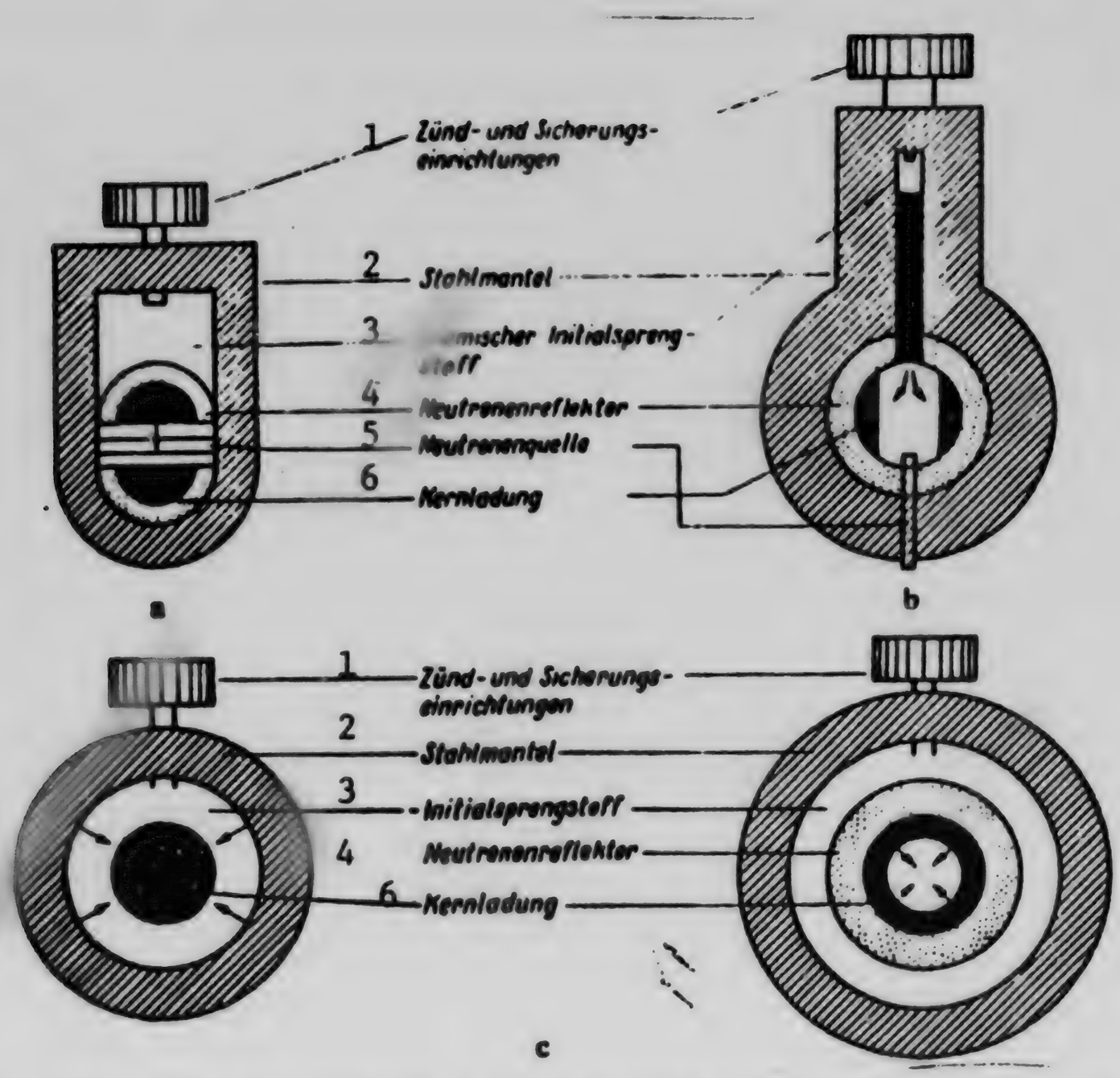


Figure 1.10. Greatly simplified illustration of the structure of nuclear fission weapons. a--Combination of two charge parts; b--Combination and deformation of charge parts; c--Implosion. Key: 1--Ignition and safety mechanisms; 2--Steel casing; 3--Chemical initial explosive; 4--Neutron reflector; 5--Neutron source; 6--Neutron charge.

Regardless of the relative information provided by these figures, they do make it clear how small the differences for n and t are for the individual detonation intensities. This is why they have an extraordinarily powerful effect on the released summary detonation energy already in case of the slightest time shifts in the course of the chain reaction. During each nuclear weapons detonation we would therefore expect a more or less strong deviation from the standard value given for the detonation intensity.

The smaller the real value of the neutron multiplication factor k is, the greater will be the required reaction time to release the energy of a certain detonation intensity k and the longer will the charge mass of the nuclear weapon have to be held together. In comparison to the values given in the tables we thus get the following: for q = 100 kt and k = 1.2; for n = 310, $t = 3.1 \cdot 10^{-6}$ sec, and $t_1 = 5.2 \cdot 10^{-7}$ sec.

In general, the total nuclear reaction time is as follows:

$$t = n \cdot t_m \text{ s} \qquad (1.14)$$

n = Number of fission cycles taking place
t_m = Average time between two fissions ($t_m = 10^{-8}$ s)

To produce a detonation energy of q kt, as we showed, it is necessary to split $z = 1.307 \times 10^{23} \cdot q$ nuclei.

The following furthermore applies in case of a neutron multiplication factor k = 2 and an initial value of $a_1 = 1$ for the chain reaction (that is to say, no separate neutron source, see below):

$$z = \frac{k^n - 1}{k - 1} = 2^n - 1 \approx 2^n \qquad (1.15)$$

It follows from this that:

$$z = 2^n = 1{,}307 \cdot 10^{23} \cdot q$$

and dissolving for n, we get the corresponding number of fission cycles as follows:

$$n = 76{,}81 + 3{,}32 \lg q \qquad (1.16)$$

According to Formula 1.14 we get the chain reaction time as follows from this:

$$t = (76{,}81 + 3{,}32 \lg q) \cdot 10^{-8}\ \text{s} \qquad (1.17)$$

Similar considerations give us approximately the following relationship for the determination of the t_1 value:

$$t_1 \approx 3{,}0 \cdot 10^{-8} \cdot q^{1/3}\ \text{s} \qquad (1.18)$$

An essential element in the detonation device of nuclear fission weapons consists of the neutron sources. They are inserted into the nuclear weapon prior to employment and can have two basic functions.

First of all, they are intended to trigger the chain reaction at the moment of ignition in an instantaneous fashion; besides, they can increase the efficiency of nuclear explosive utilization. In the last case, their purpose is to reduce the number of fission cycles required for the release of a certain detonation energy. To perform this function, the neutron sources used, however, must be highly active.

If, for example, we start with a neutron source with a yield of 10^{10} neutrons per second, then the total chain reaction time when q = 100 kt and k = 2 will be reduced by about $\Delta t = 8 \cdot 10^{-8}$ sec and, when k = 1.2, it will even be reduced by $\Delta t = 2.7 \cdot 10^{-7}$ sec. This, calculating roughly, is a decrease in the particular reaction times by about 10 percent.

As an example of a neutron source we might mention a mixture of beryllium and radium bromide powder. The neutron release then takes place according to the reaction equation:

$$^{9}_{4}Be(\alpha, n)\,^{12}_{6}C$$

At a ratio of 3-5 g beryllium per 1 g of pure radium, such a source--if the radium is in balance with its decay products--will supply about 10^7 neutrons per second for each gram of radium.

1.3.2.3. Casing

The casing of the nuclear fission weapon generally performs three independent functions:

Reception of nuclear charge and of individual elements of detonation device;

Guaranteeing the required reaction time for energy release due to a delay in the breakdown of the weapon;

Reduction in the critical dimensions of the charge mass and better utilization of nuclear explosive through its neutron-reflecting effect.

Comparisons between the mass of the nuclear charge and the total mass of a nuclear fission weapon show that they are roughly in a ratio of 1:100. This tells us that nuclear fission weapons must have a thick-walled casing made of heavy material.

According to the data in Table 1.8, the reaction times for the chain reaction are on the order of magnitude of 10^{-6} sec. During that time, the casing must prevent the premature explosion of the charge mass and thus the immediate discontinuation of the chain reaction.

Here we can note that, considering the extremely high pressure values, such as they appear immediately after ignition, the casing's ability for temporarily maintaining the chain reaction depends only on the size of its mass. The delay in the breakdown of a nuclear weapon will thus be all the longer, the more inert the casing happens to be. Here, the type of material--apart from its density--plays a subordinate role.

It has already been mentioned that neutron losses arise due to absorption and diffusion during the chain reaction. The neutron losses caused by diffusion can be considerably reduced by designing the nuclear fission weapon's casing as a neutron reflector. Such a reflector will throw a part of the neutrons coming out of the reaction zone back into it and therefore leads to a decisive reduction in the critical mass of the fissile system and thus to greater utilization of the nuclear charge.

Specifically, the effectiveness of a neutron reflector depends on the material used and its thickness. Using the same material, the effect of the reflector increases in proportion to its thickness up to a certain boundary value.

For a standard water reflector, the optimum figures are at 6 cm. For graphite, they are 50 cm and for concrete they are about 30 cm. In the case of nuclear fission weapons, the neutron reflector must directly and firmly enclose the supercritical charge mass because even the slightest intervals will severely reduce its effectiveness. This is why the implosion principle must be considered to be very favorable.

The use of neutron reflectors is particularly important in the case of nuclear weapons with smaller detonation intensity because the neutron losses here otherwise would be very heavy.

Steel, beryllium, beryllium oxides, graphite, and their mixtures are considered particularly as neutron reflectors for nuclear fission weapons. Their effectiveness will be explained with the help of some numerical examples.

In case of a spherical arrangement, the size of the critical mass for U-235, enriched to 93.5 percent, without reflector is 52 kg. Using a water reflector, we can reduce this value to 22.8 kg and if we have a reflector consisting of beryllium oxide, it can be reduced to 8.9 kg.

For almost pure Pu-239 and a spherical arrangement of the fission materials, the critical mass is around 10 kg without reflector. A beryllium reflector with a thickness of 8 cm reduces the critical mass of Pu-239 to 4.7 kg and a reflector with a thickness of 32 cm will reduce it to 2.5 kg.

By way of summary, concerning the basic approach to the fundamental structure of nuclear fission weapons in this section, we can say that it has been possible successfully through design and other measures constantly to reduce the required size of the critical mass, to increase the efficiency, and considerably to reduce the total mass of nuclear weapons as well as their dimensions. These were decisive prerequisites for the development of nuclear warheads, for example; for various artillery systems and nuclear mines.

The nuclear bombs used against Hiroshima and Nagasaki, with a detonation intensity of 20 kt TNT, each, with a nuclear charge of only 50 kg and an efficiency of 2 percent, had a total mass of about 5 t, each. At this time we may figure that a nuclear weapon of equivalent strength will have a nuclear charge of about 5 kg with an efficiency of 20 percent and a total mass of 0.3-0.5 t.

1.3.3. Nuclear Weapons of Smaller Detonation Intensity

To make nuclear weapons with smaller detonation intensity--whose equivalents partly are extremely close to the detonation intensities of conventional ammunition--there are theoretically two possibilities. One way leads via the so-called "subcaliber nuclear weapons," while the other one leads via the utilization of nuclear explosives with a very small critical mass.

During the complete fission of all atomic nuclei in a plutonium charge of 1 kg, we get a detonation energy amount of 20 kt. It follows from this that, for every kt TNT equivalent of a nuclear weapon, we only need the complete fission of 50 g plutonium. If we assume that we can figure on an average efficiency of

20 percent, then this would be tantamount to a total nuclear explosive quantity of 250 g per kt of detonation energy. It followed from the explanations given in Section 1.3.1.3. concerning the critical mass and the numerical examples given in the following sections that, to have a chain reaction, we need a critical mass whose magnitude for Pu-239 is at least 1 kg even under the most favorable conditions. But this means that the smallest detonation intensity which can be achieved on this basis--assuming the maximum utilization of the nuclear explosive--would be about 5 kt TNT.

Basically, the reduction of the efficiency of a nuclear fission weapon does not present any great difficulties. Here we only have to do the opposite, in design terms, of what we want to achieve for the maximum utilization of the nuclear charge at "normal" detonation intensities.

First of all it is possible deliberately to slow down the process of bringing about the supercritical charge arrangement at the moment of ignition. This can be achieved among other things by dropping the principle of implosion and approaching the charge parts to each other relatively slowly.

Besides, the chain reaction can be broken off in that we counter the rapid decomposition of the nuclear charge by means of a thin casing for the nuclear weapon with only minimum inertia.

Another possibility consists in the use of neutron absorbers which lead to a reduction in the size of the neutron multiplication factor k and thus the efficiency.

All of the ways sketched here--which in practice naturally have further, considerably more complicated consequences--in the final analysis boil down to the fact that, considering a magnitude of the critical mass which we cannot go below, the chain reaction is broken off prematurely and that the detonation equivalent therefore is deliberately kept small.

Subcaliber nuclear weapons are nuclear weapons whose efficiency is below the maximum possible efficiency using the same quantity of nuclear explosive.

In this way, we can achieve nuclear fission weapons with detonatio ntensities between several hundreds of tons of TNT and several kilotons of TN h a justifiable effort.[34]

A decisive prerequisite for the mass production of nuclear fission weapons with small and very small detonation intensities on the basis of relatively poor utilization of the particular nuclear charges was the presence of sufficient supplies of fissile materials.

This is why subcaliber nuclear weapons--whose construction was basically possible from the very beginning--did not appear until the early 1960's. At that time the armament of the armies already included nuclear weapons systems for the most varied purposes with a broad scale of detonation intensities. On top of that we have the fact that methods for obtaining and processing nuclear explosives had by that time matured quite extensively.

The production of nuclear weapons on the basis of the "subcaliber principle" does not only have an uneconomical side. There is also a series of other aspects which make it appear impractical to use this method even for extremely small detonation equivalents.

According to American data, for example, in a series of tests in the autumn of 1957, nuclear charges with detonation intensities of only 0.001 kt, 0.006 kt, and 0.036 kt were tested. With such low detonation intensities, it is very difficult to determine the efficiency from the design angle. In other words, this means that, as the detonation intensity becomes smaller, the possible deviations from the standard value given will become bigger all the time. It must furthermore be kept in mind that, looking at subcaliber nuclear weapons, the share of unsplit nuclear charges out of the total quantity of radioactive detonation products is very high. But it so happens that Pu-239 is not only a very long-lived alpha-active radionuclide but moreover is biologically very dangerous and chemically highly toxic.

So far we have had only unofficial publications on the use of fission materials with a critical mass magnitude which is far below that of Pu-239, for the production of nuclear weapons with extremely low detonation intensities. Accordingly, Californium, for example, is supposed to be useful for these purposes, specifically, the isotopes Cf-294 and Cf-251.

The critical mass is given here only at 1.5 g without reference to a specific nuclide. Using this value as basis, this would mean that, figuring on a maximum efficiency of 20 percent and a minimum efficiency of only 0.1 percent, one could achieve detonation intensities in the range of 0.06-0.00003 kt.

The resultant possible weapons-engineering aspects are quite obvious. But they would be of basic military significance only if the suitable Californium isotopes could be produced in large quantities with a justifiable economic effort. This however obviously is not the case.[35]

1.3.4. Energy Release during Detonation of Nuclear Fission Weapon

The internal detonation process in a nuclear fission weapon starts with the triggering of the chain reaction due to the conversion of the nuclear charge from the subcritical to the supercritical state. The reaction time is extremely short and, as we said before, is something like 10^{-6} sec.

In our comments on the nuclear charge of a nuclear fission weapon in Section 1.3.2.1., we assumed--in deriving Formula 1.11--that, on the average, for each nucleus split, an energy amount of 200 Mev is released. This can be shown in detail if we compare the masses present before and after nuclear fission and if we compute the energy belonging to the resultant mass defect.

Among the many possibilities for nuclear fission we might make reference here to the example illustrated in Figure 1.8, below.

Table 1.9. Example of Energy Balance during Fission of U-235 Nucleus

	Mass number	Relative nuclear mass ME
(1) Sum of nuclear masses prior to fission		
(1.1) Parent nucleus U-235	235	235.0432
(1.2) Triggering neutron	1	1.00865
(1.3) Σ (1.1) + (1.2)	236	236.05097
(2) Sum of nuclear masses after fission, after completion of radioactive decay(1)		
(2.1) neodymium nucleus formed, $^{143}_{60}Nd$	143	142.90862
(2.2) zirconium nucleus formed, $^{90}_{40}Zr$	90	89.90430
(2.3) 3 fission neutrons, 3 $^{1}_{0}n$	3	3.02595
(2.4) Σ (2.1) to (2.3)	236	235.83887

(3) Size of mass defect: (1.3) to (2.4) $\Delta m = 0.2121$
Because 1 ME corresponds to an energy of 931 MeV, it follows for Δm:
$E_{s_p} = 0.2121 \cdot 931$ MeV = 197 MeV(2)

(1) The original nucleus fragments $^{143}_{56}Ba$ and $^{90}_{36}Kr$ are converted into $^{143}_{60}Nd$ or $^{90}_{40}Zr$ as a result of four successive beta decay processes. The balance given in the table thus contains the energy released as a result of the radioactive decay of the nuclear fragments.
(2) In case of a different type of nuclear fission of U-235, the energy is partly above this value so that the 200 MeV figured as mean value relate to the entire fission product mixture.

The nuclear energy of 200 Mev per split nucleus is directly distributed over the moment of detonation and the following interval of radioactive decay of the fission products. It appears here in various energy forms. Table 1.10 presents an overview.

Table 1.10. Energy Distribution during Fission of Heavy Nuclei

Energy form	Energy quantity MeV	%
In the process of nuclear fission		
kinetic energy of fission products	165± 5	82.5
kinetic energy of neutrons	5±0.5	2.5
energy of gamma radiation	7±1	3.5
In the course of radioactive decay of fission products		
energy of beta radiation	7±1	3.5
energy of neutrinos	10	5.0
energy of gamma radiation	6±1	3.0
Total energy per fission	200±6	100

The biggest part of the detonation energy is converted into thermal energy. This heats the entire charge mass to extremely high temperatures. The developing positive nuclear fragments repel each other and move away from each other at fast speed. During collision with other nuclei in the charge, their kinetic energy is primarily converted mainly into heat. The unsplit part of the nuclear charge and the fission products formed are heavily ionized due to the gamma quantums and neutrons released during nuclear fission and are in fact stripped of their electron envelope. The subsequent recombinations lead to the emission of light radiation and x-rays whose energy likewise is consumed to the extent of more than 90 percent to heat the reaction zone.

In this way, very high energy concentrations are achieved during detonation.

According to Formula 1.10., the equivalent energy amount of $2.614 \cdot 10^{25}$ Mev corresponds to a detonation intensity of 1 kt. For this we need about 50 g nuclear explosive (1.12). Assuming a density of 19 g cm^{-3}, we can calculate the corresponding charge volume at about 2.6 cm^3. For an efficiency of 100 percent, it then follows. for the magnitude of the energy concentration, that we have: $C_{Det} \approx 2{,}6 \cdot 10^{25}$ MeV : 2,6 $cm^3 \approx 10^{25}$ MeV cm^{-3} and in case of $\eta = 0{,}2$ $C_{Det} \approx 2 \cdot 10^{24}$ MeV cm^{-3}.

In general we can thus show that the initial energy concentration in nuclear fission weapons as a function of the efficiency is on the order of magnitude of 10^7 kcal cm^{-3}.[36]

Table 1.11. Comparison of Energy Concentrations from Detonations of Nuclear Fission Weapons and the Explosive TNT

	Nuclear weapon	TNT
Energy concentration, kcal cm^{-3}	10^7	1.5
Maximum temperature in reaction zone °K	$30 \cdot 10^6$	$5 \cdot 10^3$
Maximum pressure in reaction zone, atm abs	$20 \cdot 10^9$	$2 \cdot 10^5$

The maximum temperature in the reaction zone can approximately be estimated as follows:

$$T = \sqrt[4]{\frac{E_{Det}}{\theta \cdot F_{KL} \cdot t_1}} \qquad (1.19)$$

T--Thermodynamic temperature/°K
E_{Det}--Detonation energy/erg; see Formula 1.9
θ--Constant ($\theta = 5.7 \cdot 10^{-5}$ erg $cm^{-2} s^{-1} °K^{-4}$)
F_{KL}--Surface of nuclear charge/cm^2 ($F_{KL} \approx 30 \cdot q^{2/3}$)
t_1--Time/sec during which 90 percent of the detonation energy are released; see Table 1.8 or Formula 1.18.

The maximum pressure in the reaction zone can be estimated roughly as follows:

$$p = 9{,}87 \cdot 10^{-7} \cdot m \cdot k \cdot T \qquad (1.20)$$

p--Maximum pressure in reaction zone/atm abs
m--Number of particles per cm^3 gas/[illegible]/cm^3
k--Boltzmann constant ($k = 1.38054 \cdot 10^{-16}$ erg $°K^{-1}$)
T--Thermodynamic temperature/°K

The formula given for the calculation of the maximum pressure in the reaction zone goes back to the kinetic gas theory according to which the gas pressure is roughly proportional to the number of particles per volume unit and the thermodynamic temperature.[37] For the computation we can assume roughly the following:

$$m \approx 4 \cdot 10^{24} cm^{-3}.$$

Review Questions

1.11. What fundamental connection is there between nuclear binding energy and mass effect?